Civil Engineering

Construction Materials

Comprehensive Theory

with **Solved Examples** and **Practice Questions**

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CHAPTER 01

Cement

1.1 Introduction

- Cement is an extremely fine material having adhesive and cohesive properties which provide a binding medium for the discrete ingredients.
- The cement is a product obtained by pulverizing (to make into a powder form) clinker formed by calcinating the raw material preliminary consisting of Lime (CaO), Silicate (SiO_2), Alumina (Al_2O_3) and Iron oxide (Fe_2O_3).
- When cement is mixed with water it forms a paste which binds aggregates (fine and coarse) together to form a hard durable mass called concrete.
- The cement which is fine in nature is assume to have good setting property, finer the grains of the cement more is the strength of cement.
- The cement is having good heat of hydration due to which it sets early as compared to other binding material like lime.
- The cement experiences the exothermic chemical reaction when comes in a contact with water.
- The cement is assume to have a specific gravity of 3.15.
- Joseph Aspdin manufactured cement and called it Portland cement because when it hardened, it produced a material resembling stone from the quarries near Portland in England.
- During grinding of clinker, "Gypsum or plaster of Paris" is added to prevent flash setting of the cement. The amount of gypsum is about 3 to 5 per cent by weight of clinker. It also improves the soundness of cement.
- The common calcareous materials are lime stone, chalk, marine shell and marl.
- The argillaceous materials are clay, shale, slate and selected blast furnace slag.
- The processes used for the manufacture of cement can be classified as dry and wet.
- The ideal net weight of cement bag is 50 kg and volume of 0.035 m^3.

1.2 Cement and Lime

Following points of differences may be noted between ordinary cement and lime:

1. The cement is used for the gain of early strength whereas lime gains the strength slowly.
2. The cement and lime color are different.

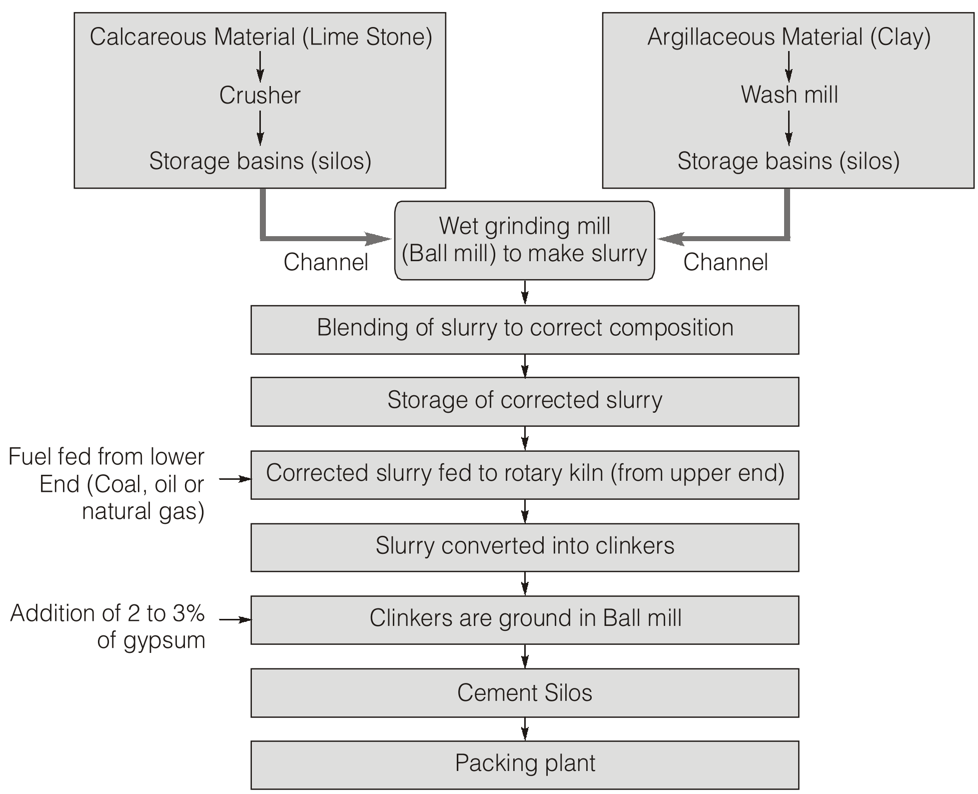
3. The cement and lime both is a binding material having good ultimate strength but lime experiences less early strength as compare to cement.

1.3 Manufacturing of Cement

- The cement is manufactured by integrating the calcareous component and argillaceous component in ratio of 3 : 1.
- The calcareous component can be **limestone, chalk, marine shells, marl** whereas argillaceous components can be **shale, clay, blast furnace slag, slate**.
- The calcareous component is used to derive the ingredient called lime whereas the argillaceous component composed of silica, alumina, iron oxide and other impurities.

(a) Wet process:

- It is the old method of manufacturing which is now a days obsoleted.
- It is a costly method of manufacturing because it requires higher degree of fuel consumption, power consumption.
- In this process the preheater is not used.

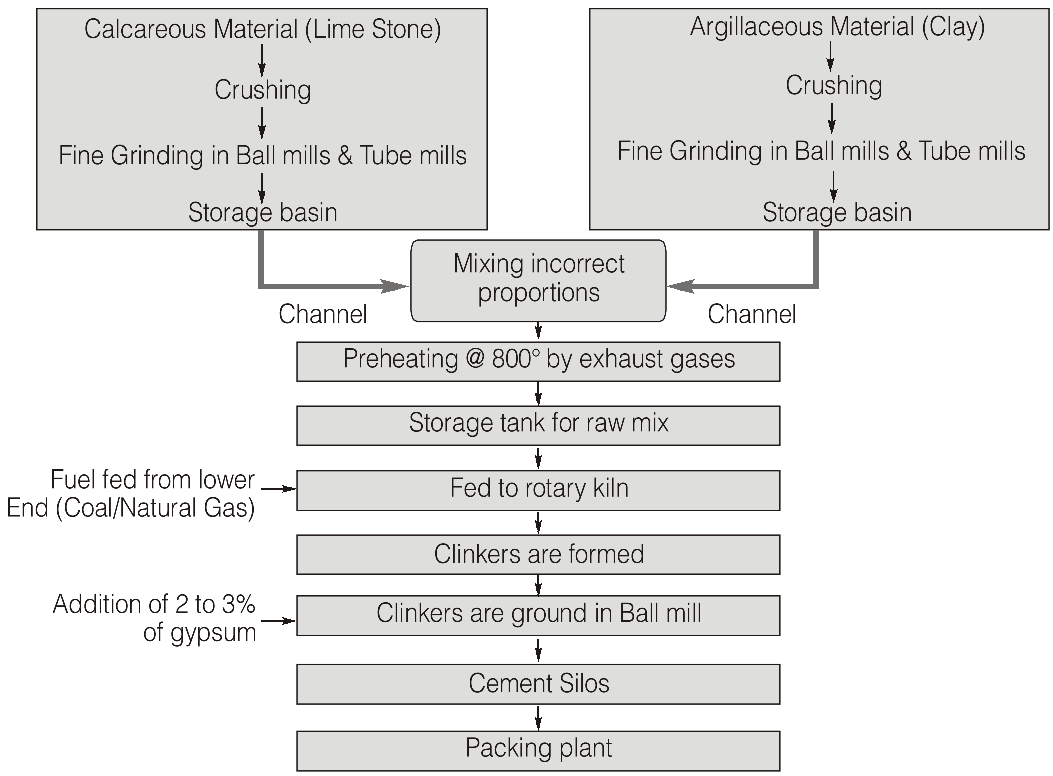


Flow diagram of wet process

(b) Dry process:

- It is a new method of manufacturing which is trending now-a-days.
- The fuel consumption, power consumption has been reduced to a greater extent by modifying the wet process.

Dry process:



Flow diagram of dry process

- In a dry process, first calcareous components (limestone) and argillaceous component (clay or shale) is reduced in size about 25 mm in a crushers separately in a ball mill or tube mill.

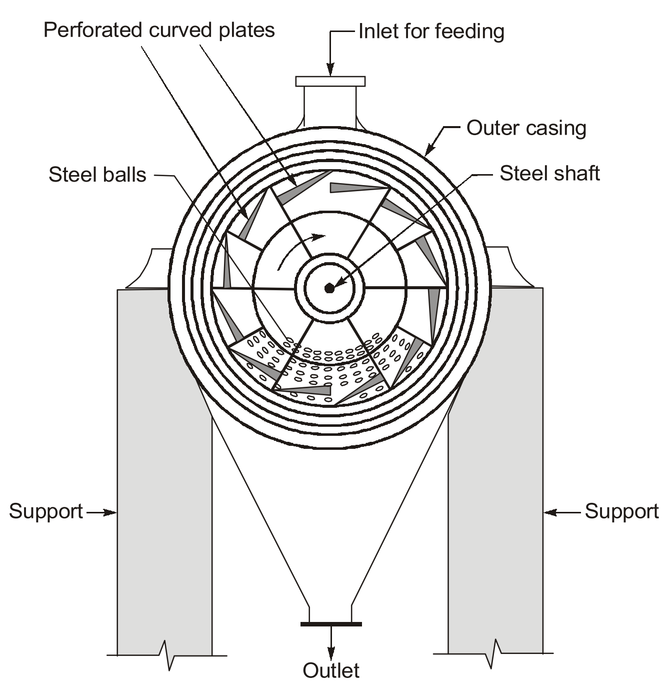


Fig. *Vertical Section of a Ball Mill*

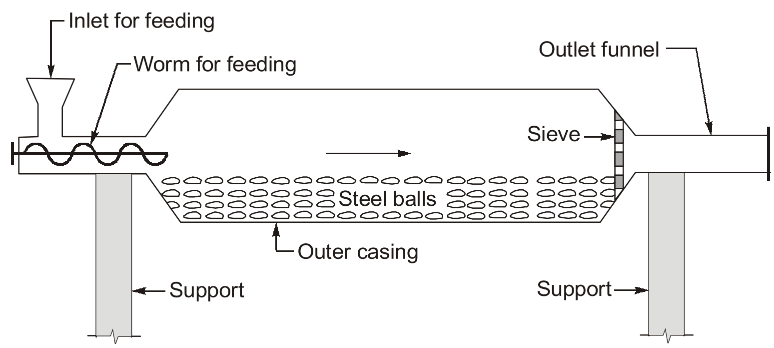


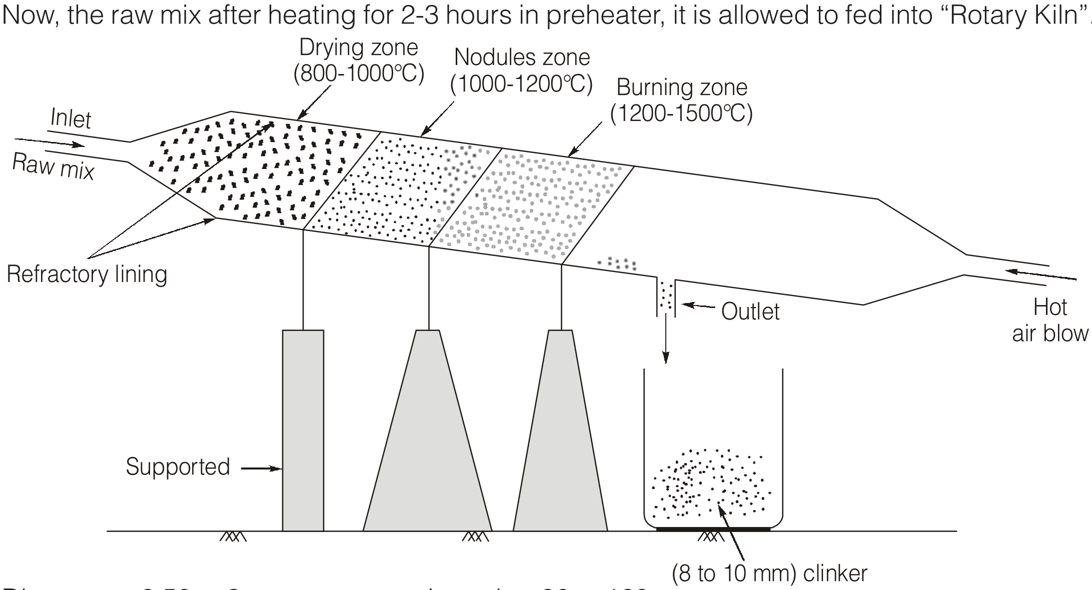
***Fig.** Longitudinal Section of a Tube Mill*

- The calcareous component and argillaceous component after grinding are mixed with each other in a correct proportion and made it ready for next operation in rotary kiln.
- Before feeding into rotary kiln the raw mix is allowed in preheater at a temperature of 850°C which reduces the burning time of raw mix in rotary kiln.

NOTE

The crushed material is checked for content of $CaCO_3$, Lime, Alumina, Silica, Fe_2O_3. Any component found short in quarried material is added separately. **e.g.** Silica is less than crushed sandstone is separately added to raw mix and if lime is less then high grade limestone is crushed and added into raw mix.

- Now, the raw mix after heating for 2-3 hours in preheater, it is allowed to fed into "Rotary Kiln".



Diameter = 2.50 to 3 metre   Length = 90 to 120 metre

Volume ≈ 706.3 m^3 Laid Gradient = 1 in 25 to 1 in 30

Revolution = 3 round/min about longer axis.

- **Nodule Zone:** In this zone calcination of limestone occurs and limestone get disintegrated into two parts i.e. lime and carbon dioxide.

$$CaCO_3 \xrightarrow[\text{Calcination}]{\text{Heat}} CaO + CO_2(\uparrow)$$

As the CO_2 is evaporated from the raw mix, the raw mix get converted into nodules.

- **Burning Zone:** In this zone the ingredients of calcareous and argillaceous component i.e. lime, silica, alumina, iron oxide etc. get united with each other at a very high temperature and this process is called fusion.

$$2CaO + SiO_2 \longrightarrow Ca_2SiO_4 = C_2S \text{ (Dicalcium Silicate)}$$

$$3CaO + SiO_2 \longrightarrow Ca_3SiO_5 = C_3S \text{ (Tricalcium Silicate)}$$

$$3CaO + Al_2O_3 \longrightarrow Ca_3Al_2O_6 = C_3A \text{ (Tricalcium Aluminate)}$$

$$4CaO + Al_2O_3 + Fe_2O_3 \longrightarrow Ca_4Al_2Fe_2O_{10} = C_4AF \text{ (Tetra-calcium Alumino-ferrite)}$$

  The product obtained from rotary kiln is called clinker which is composed of major compound (Bougue's Compound) and Minor Compound i.e. Alkalies (Soda and Potash).
- The clinker composed of (Bougue's compound) and Minor compounds i.e. Alkalies (Soda and Potash)
- The clinker is having flash set property i.e. quick setting property when it comes in contact with moisture. Therefore, the retarder is added to the clinker by its weight i.e. 2 to 3 percent.
- The retarder is admixture which delays the setting time of the cement clinker.
- The ultimately binding material is C – S – H gel i.e. Calcium silicate hydrate gel which is formed when the hydration of cement takes place.

Raw material for cement	Limestone, clay shale (calcareous and argillaceous material)
↓	
Oxide composition in raw materials	CaO SiO_2 Al_2O_3 Fe_2O_3
On burning ↓	clinker formed
Compound composition	C_3S C_2S C_3A C_4AF
On ↓	grinding clinker
Portland cements	Various types
On ↓	hydration
Products of hydration	C – S – H gel + $Ca(OH)_2$

1.3.1 Composition of Cement Clinker

The principal mineral compounds in Portland cement	Formula	Name	Symbol	Percentage
1. Tricalcium silicate	$3CaO \cdot SiO_2$	Alite	C_3S	30-50%
2. Dicalcium silicate	$2CaO \cdot SiO_2$	Belite	C_2S	20-45%
3. Tricalcium aluminate	$3CaO \cdot Al_2O_3$	Celite	C_3A	8-12%
4. Tetracalcium alumino ferrite	$4CaO \cdot Al_2O_3 \cdot Fe_2O_3$	Felite	C_4AF	6-10%

- Besides major compounds, minor compounds are also formed that are: Soda (Na_2O) and Potash (K_2O). These two minor compounds i.e. Soda and Potash are responsible for **Efflorescence** in a cement concrete and cement mortar.

Efflorescence: Efflorescence is the migration of the salt to the surface of porous material, where it forms a coating. This process involves the dissolving of internally held salt in water. The water with the salt migrates to the surface, then evaporates, leaving a coating of salt.

- It is found that ordinary cement achieves **70 percent of its final strength in 28 days** and **90 percent in 1 year**.
- The strength in a cement is majorly depends upon the Bougue's compound. The properties of Portland cement varies significantly with the proportion of four Bougue's compounds.

1. **Tricalcium Silicate C_3S – (30 to 50%)**
   - It is considered as a very good strength compound. It enables the clinker to grind easily.
   - It hydrates rapidly generates high heat and develop early hardness and strength.
   - It increases the resistance to **freezing and thawing.**
   - Raising of C_3S content beyond specific limit the heat of hydration increases.
   - The hydration of C_3S is mainly responsible for 7 days strength and hardness.
   - The C_3S is responsible not only for the gain of strength at early days but contributes considerably upto 28 days.
   - It is the only compound which has maximum contribution in 28 days strength, it is responsible for gain of strength from 24 hours to 28 days where it contributes (max) upto 14 days.
   - The heat of hydration is 500 J/gm.
2. **Dicalcium Silicate C_2S – (20 to 45%)**
   - It hydrates and hardens slowly and takes long time to add to the strength. It is responsible for **ultimate strength**.
   - It imparts **resistance to chemical attack**.
   - Raising C_2S content in cement reduces the **early strength**.
   - Raising C_2S content, decreases the resistance to freezing and thawing at early ages and decreases heat of hydration.
   - At early days C_2S has little influence on strength and hardness, where after a year its contribution is same as C_3S in strength and hardness.
   - The C_2S is a stable compound because in a low heat cement C_2S content is more as low heat cement is stable cement with respect to durability of structure.
   - The contribution of C_2S starts from 14 days and remains upto 1 year and or so.
   - After 28 days the gain of strength is due to C_2S.
   - The heat of hydration 260 J/gm.
3. **Tricalcium Aluminate C_3A (8 to 12 %)**
   - It rapidly reacts with water and is responsible for flash set of finely grounded clinker.
   - The flash set property of cement clinker is prevented by adding a retarder gypsum 2% to 3%.
   - Least stable compound because it is responsible for maximum heat of hydration and very less durable with respect to susceptible cracks in structure.
   - Any cement having C_3A content more is liable for sulphur attacks.
   - It contributes in 24 hours strength after addition of water but it contribute less.
   - It has heat of hydration 865 J/gm.

4. Tetra-calcium Aluminate Ferrite C4AF (6– 10%)

- It is also responsible for high heat of hydration as compare to C_2S and but less than C_3A.
- Its contribution in strength is very less.
- It is having contribution within 24 hours of adding water to the cement.
- The heat of hydration 420 J/gm.

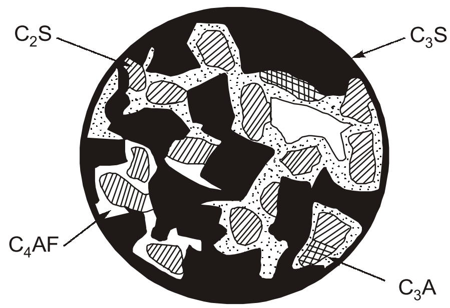


Fig. Schematic representation of the composition of Portland cement

NOTE

- The rate of hydration is increased by an increase in fineness of cement. However, total heat evolved is the same. The rate of hydration of the principal compounds is shown in figure and will be in the following descending order. $C_4AF > C_3A > C_3S > C_2S$

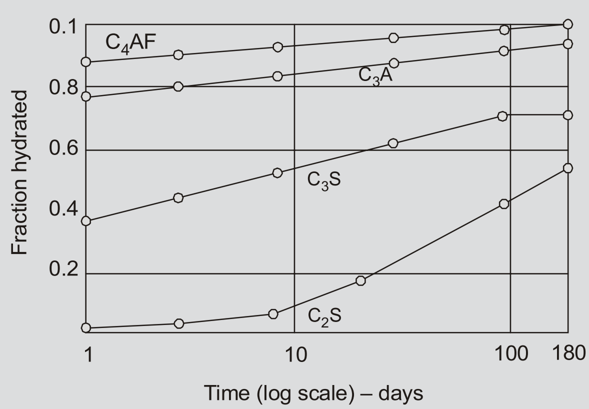


***Fig.** Rate of Hydration of Pure Compounds*

- Rate of heat evolution of Bougue compound, if equal amount of each is considered will be in following descending order

  C_3A (865 J/gm) > C_3S (865 J/gm) > C_3AF (420 J/gm) > C_2S (260 J/gm).

Compound	Heat of hydration at the given age (J/g)		
	3 days	90 days	13 years
C_3S	242.44	434.72	509.96
C_2S	50.16	175.56	246.62
C_3A	886.16	1299.98	1354.32
C_4AF	288.42	409.64	426.36

Heat of Hydration

- Development of strength of four Bougue's compounds of cement with age.

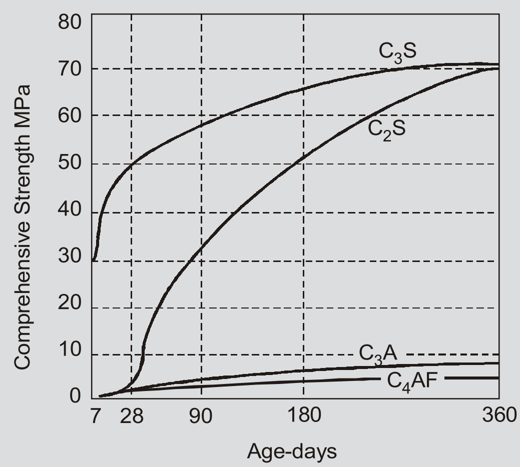


Fig. *Development of Strength of Pure Compounds*

1.3.2 Functions of Various Cement Ingredients

- The relative proportions of thee oxide compositions are responsible for influencing the various properties of cement.
- Consequently, free lime will exist in the clinker and will result in an unsound cement. An increase in silica content at the expense of alumina and ferric oxide makes the cement difficult to fuse and form clinker.
- Rate of setting of cement paste is controlled by regulating the ratio $SiO_2/(Al_2O_3 + Fe_2O_3)$
- When development of heat of hydration is undesirable, the silica content is increased to about 21 per cent. and the alumina and iron oxide contents are limited to 6 per cent each.
- Resistance to the action of sulphate waters is increased by raising further the silica content to 24 per cent and reducing the alumina and iron contents in 4 per cent each.
- Small percentage of iron oxide renders the highly siliceous raw materials easier to burn.

Constituents	Percentage	Average percentage
Lime (CaO)	62 to 67%	62
Silica (SiO_2)	17 to 25%	22
Anumina (Al_2O_3)	3 to 8%	5
Calcium Sulphate ($CaSO_4$)	3 to 4%	4
Iron oxide (Fe_2O_3)	3 to 4%	3
Magnesia (MgO)	0.1 to 3%	2
Sulphur	1 to 3%	1
Soda and Potash ($Na_2O + K_2O$)	0.5 to 1.3%	1

1. **Lime (CaO):** This is the important ingredient of cement and its proportion is to be carefully maintained. The lime in excess makes the cement unsound and causes the cement to expand and disintegrate. On the other hand, if lime is in deficiency, the strength of cement is decreased and it causes cement to set quickly.

2. **Silica (SiO_2):** This is also an important ingredient of cement and it imparts strength to the cement due to the formation of dicalcium and tricalcium silicates. If silica is present in excess quantity, the strength of cement increases but at the same time, its setting time gets prolonged.
3. **Alumina (Al_2O_3):** This ingredient imparts quick setting property to the cement. It acts as a flux and it lowers the clinkering temperature. However high temperature is essential for the formation of a suitable type of cement and hence the alumina should not be present in excess amount as it weakens the cement.
4. **Calcium Sulphate ($CaSO_4$):** This ingredient is in the form of gypsum and its function is to increase the initial setting time of cement.
5. **Iron Oxide (Fe_2O_3):** This ingredient imparts colour, hardness and strength to the cement.
6. **Magnesia (MgO):** This ingredient, if present in small amount, imparts hardness and colour to the cement. A high content of magnesia makes the cement unsound.
7. **Sulphur (S):** A very small amount of sulphur is useful in making sound cement. If it is in excess, it causes unsoundness in cement.
8. **Alkalies:** The most of the alkalies present in raw materials are carried away by the flue gases during heating and the cement contains only a small amount of alkalies. If they are in excess in cement, they cause a number of troubles such as alkali-aggregate reaction, efflorescence and staining when used in concrete, brickwork or masonry mortar.

1.4 Hydration of Cement

- The chemical reactions that take place between cement and water is referred to as hydration of cement.
- The hydration of cement can be visualized in two ways viz. "through solution" and "solid state" type of mechanisms
- The reaction of cement with water is exothermic i.e. it liberates a considerable quantity of heat and this liberated heat is called as **heat of hydration**.
- The hydration process is not an instantaneous one. The reaction is faster in the early periods and continues indefinitely at a decreasing rate.
- During hydration, C_3S and C_2S react with water and calcium silicate hydrate (C-S-H) is formed along with calcium hydroxide [$Ca(OH)_2$].
- Calcium silicate hydrate is the most important product of hydration and it determines the good properties of concrete.
- $2(3CaO \cdot SiO_2) + 6H_2O \rightarrow 3CaO \cdot 2SiO_2 \cdot 2H_2O + 3Ca(OH)_2$

  or it can be written as:

$$2C_3S + 6H \rightarrow C_3S_2H_3 + 3Ca(OH)_2$$
$$100 + 24 \rightarrow 75 + 49$$

The corresponding weights involved are
Similarly,

$$2(2CaO \cdot SiO_2) + 4H_2O \rightarrow 3CaO \cdot 2SiO_2 \cdot 3H_2O + Ca(OH)_2$$

or it can be written as:

$$2C_2S + 4H \rightarrow C_3S_2H_3 + Ca(OH)_2$$
$$100 + 21 \rightarrow 99 + 22$$

The corresponding weights involved are:

$$2C_3S + 6H \longrightarrow C_3S_2H_3 + 3Ca(OH)_2$$

$$2C_2S + 4H \longrightarrow C_3S_2H_3 + Ca(OH)_2$$

Permissible Limits for Impurities in Water

Impurity	Permissible Limits
Organic	200 mg/*l*
Inorganic	3000 mg/*l*
Sulphates (So_4^{-2})	400 mg/*l*
Chlorides (Cl^-)	2000 mg/*l* for plain concrete work, 500 mg/*l* for reinforced concrete work
Suspended matter	2000 mg/*l*

- It can be seen from the above reactions that C_3S produces a comparatively less quantity of calcium silicate hydrate and more quantity of calcium hydroxide than that formed in the hydration of C_2S.
- Calcium hydroxide is not a desirable product in the concrete mass as it is soluble in water and gets leached out thereby making the concrete porous, particularly in hydraulic structures.
- C_2S reacts rather slowly and it is responsible for strength of concrete at later stage. It produces less heat of hydration.
- The lack of durability of concrete is on account of the presence of calcium hydroxide.
- The calcium hydroxide also reacts with sulphates present in soils or water to form calcium sulphate which further reacts with C_3A and cause deterioration of concrete. This is known as **sulphate attack**.
- The only advantage of calcium hydroxide is that being alkaline in nature it maintains pH value around 13 in the concrete which resists the corrosion of reinforcements.
- From the view point of hydration, it is convenient to discuss C_3A and C_4AF together because the products formed in the presence of gypsum are similar. Gypsum and alkalies go into solution quickly and the solubility is depressed. Depending upon the concentration of aluminate and sulphate ions in the solution, the precipitating crystalline product is either calcium aluminate trisulphate hydrate or calcium aluminate monosulphate hydrate. The calcium aluminate trisulphate hydrate is known as Ettringite.
- It has been estimated that on an average 23% of water by weight of cement is required for chemical reaction with Portland cement compounds. This 23% of water chemically combines with cement, and therefore it is called as bound water.
- A certain quantity of water is imbibed within the gel pores. This water is known as gel water. The bound water and gel water are complimentary to each other.
- It has been estimated that about 15% water by weight of cement is required to fill up the gel pores.
- Therefore, a total of 38% of water by weight of cement is required for the complete chemical reactions and occupy the space within gel pores.
- If water equal to 38% by weight of cement is only used then it can be noticed that the resultant paste will undergo full hydration and no extra water will be available for the formation of undesirable capillary cavities.
- **If more than 38% of water is used, then excess water will cause undesirable capillary cavities which ultimately reduces the strength of the cement concrete.**

Objective Brain Teasers

Q.1 The main ingredients of Portland cement are
(a) line and silica
(b) line and alumina
(c) silica and alumina
(d) line and iron

Q.2 The constituent of cement which is responsible for all the undesirable properties of cement is
(a) dicalcium silicate
(b) tricalcium silicate
(c) tricalcium aluminate
(d) tetra calcium alumino ferrite

Q.3 Le Chatelier's device is used for determining the
(a) setting time of cement
(b) soundness of cement
(c) tensile strength of cement
(d) compressive strength of cement

Q.4 Addition of pozzolana to ordinary Portland cement increase
(a) bleeding
(b) shrinkage
(c) permeability
(d) heat of hydration

Q.5 Proper amount of entrained air in concrete results in
1. better workability
2. better resistance of freezing and thawing
3. lesser workability
4. less resistance to freezing and thawing

The correct answer is
(a) 1 and 2 (b) 1 and 4
(c) 2 and 3 (d) 3 and 4

Q.6 The most commonly used retarder in cement is
(a) gypsum
(b) calcium chloride
(c) calcium carbonate
(d) none of the above

Q.7 The most common admixture which is used to accelerate the initial set of concrete is
(a) gypsum
(b) calcium chloride
(c) calcium carbonate
(d) none of these

Q.8 According to IS specifications, the compressive strength of ordinary Portland cement after three days should not be less than
(a) 7 MPa (b) 11.5 MPa
(c) 26 MPa (d) 21 MPa

Q.9 Increase in fineness of cement
(a) reduces the rate of strength development and leads to higher shrinkage
(b) increases the rate of strength development and reduces the rate of deterioration
(c) decreases the rate of strength development and increases the bleeding of cement
(d) increases the rate of strength development and leads to higher shrinkage

Q.10 The initial setting time for ordinary Portland cement as per IS specifications should not be less than
(a) 10 minutes (b) 30 minutes
(c) 60 minutes (d) 600 minutes

Answers

1. (a)	2. (c)	3. (b)	4. (b)	5. (a)
6. (a)	7. (b)	8. (c)	9. (d)	10. (b)

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